ATTENUATION AND DISPERSION OF ULTRASONIC WAVES IN ROLLED ALUMINUM

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INTRODUCTION

Measurements of ultrasonic velocity and attenuation can provide important tools in characterizing the microstructure of materials [1]. For example, velocity measurements can provide information on crystallographic texture while attenuation measurements provide information of grain size. For selected cases, a strong theoretical base is in place [2-4]. However, when both texture is present and the grains are elongated, such is not the case. The purpose of this paper is to describe theoretical calculations addressing this problem. Aluminum is chosen as the material because of interests in using ultrasound to monitor its recrystallization [5].

THEORY

The calculations are based on the model of Stanke and Kino [2] as interpreted by Ahmed and Thompson [3,4]. Thus we seek the solution to a stochastic wave equation within the context of the second order Keller approximation. As was shown in Ref. [3], this can be rewritten in the form of a generalized Christoffel equation

$$\left[\Gamma_{ik} - \rho\frac{\omega^2}{k^2}\delta_{ik}\right]\hat{u}_k = 0 \tag{1}$$

where the Christoffel tensor is a frequency dependent quantity given by

$$\Gamma_{ik} = \Big\{C^o_{ijkl} + \varepsilon\langle\Delta_{ijkl}\rangle + \varepsilon^2\Big[\langle\Delta_{ij\alpha\beta}\Delta_{\gamma\delta kl}\rangle - \langle\Delta_{ij\alpha\beta}\rangle\langle\Delta_{\gamma\delta kl}\rangle\Big]$$

$$\mathrm{x}\int_v G_{\alpha\gamma}(\vec{s})\Big[W(\vec{s})e^{ik\vec{s}.\hat{k}}\Big]_{,\beta\delta}\,dv\Big\}\hat{k}_j\hat{k}_l\,. \tag{2}$$

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where C^{o}_{ijkl} is the average elastic stiffness tensor of the untextured medium (Voigt average), $\varepsilon \Delta^{\xi}_{ijkl}(r) = C^{\xi}_{ijkl}(r) - C^{o}_{ijkl}$ is the perturbation of the elastic stiffness in a particular member of the ensemble from that average value, $\langle \cdots \rangle$ denotes an ensemble average, $G_{\alpha\gamma}(\bar{s})$ is a Green's function, and W(s) is the geometrical autocorrelation function, assumed to have the form

$$W(s) = e^{-2s/\bar{d}\sqrt{1+\left(\bar{d}^2/\bar{h}^2-1\right)\cos^2\theta}} \tag{7}$$

where $\bar{d}$ is the mean grain diameter in the rolling direction and $\bar{h}$ is the mean grain height in the normal direction. W(s) may be thought of as describing the probability that two points fall in the same grain and is assumed to be rotationally symmetric about the normal direction. It's form is sketched in Figure 1.

In the calculation, the material was assumed to be described by the single constant elastic constants C_{11} = 103.4 GPa, C_{12} = 571 GPa, C_{44} = 28.6 GPa and density 2760 kg/m^3. The texture was taken to be a rolling texture of a sample which had been previously studied [6], characterized by the orientation distribution coefficients W_{400} = -0.0009425, W_{420} = -0.002155, and W_{440} = -0.005149. The preferred orientation defined by these values was used in the computation of the ensemble averages of the elastic constants.

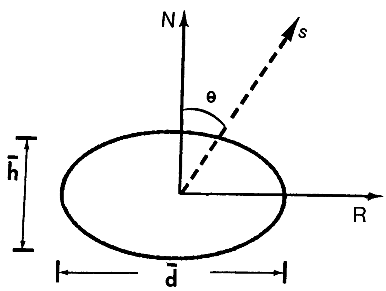

Fig. 1. Definition of Parameters Defining Grain Shape.

NUMERICAL RESULTS

Calculations were made of the longitudinal wave attenuation and velocity, as a function of frequency, for waves propagating in the normal and rolling directions. As an example Fig. 2 presents the attenuation for waves propagating in the normal direction for grains of four aspect ratios, ranging from equiaxed to pancake shaped. Both linear and logarithmic plots are provided to clearly illustrate the behavior in the Rayleigh, stochastic and geometrical regimes, as has been discussed elsewhere [2-4]. It is interesting to note how the ordering of the curves changes with aspect ratio. For a fixed diameter d, the equiaxed grains have the greatest attenuation for waves propagating in the Rayleigh regime while the pancake shaped grains have the highest attenuation for waves in the geometrical regime. This result

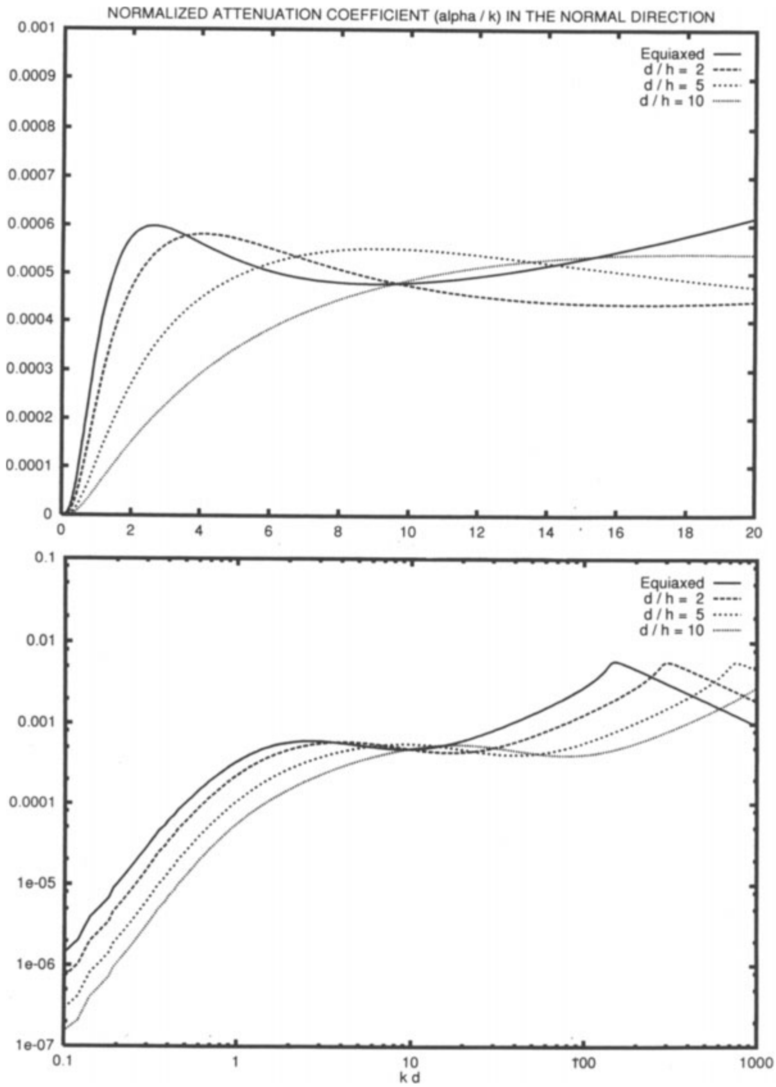

Fig. 2. Normalized Attention of Longitudinal Waves Propagating in the Normal Direction.

can be understood in terms of the fact that grain volume and number of grain boundaries respectively control the attenuation in the two regimes. Figure 3 shows the corresponding velocity results. Calculations for waves propagating in the rolling direction show the same qualitative form.

Figure 4 compares the attenuations of waves propagating in the two directions for equiaxed grains and with pancake shaped grains having an aspect ratio of 10. The former illustrate the effects of texture only while the latter introduce the additional effects of grain elongation. Figure 5 shows the corresponding effects of propagation direction and grain shape on velocity. Here the primary effect is an offset due to the anisotropic elastic constants.

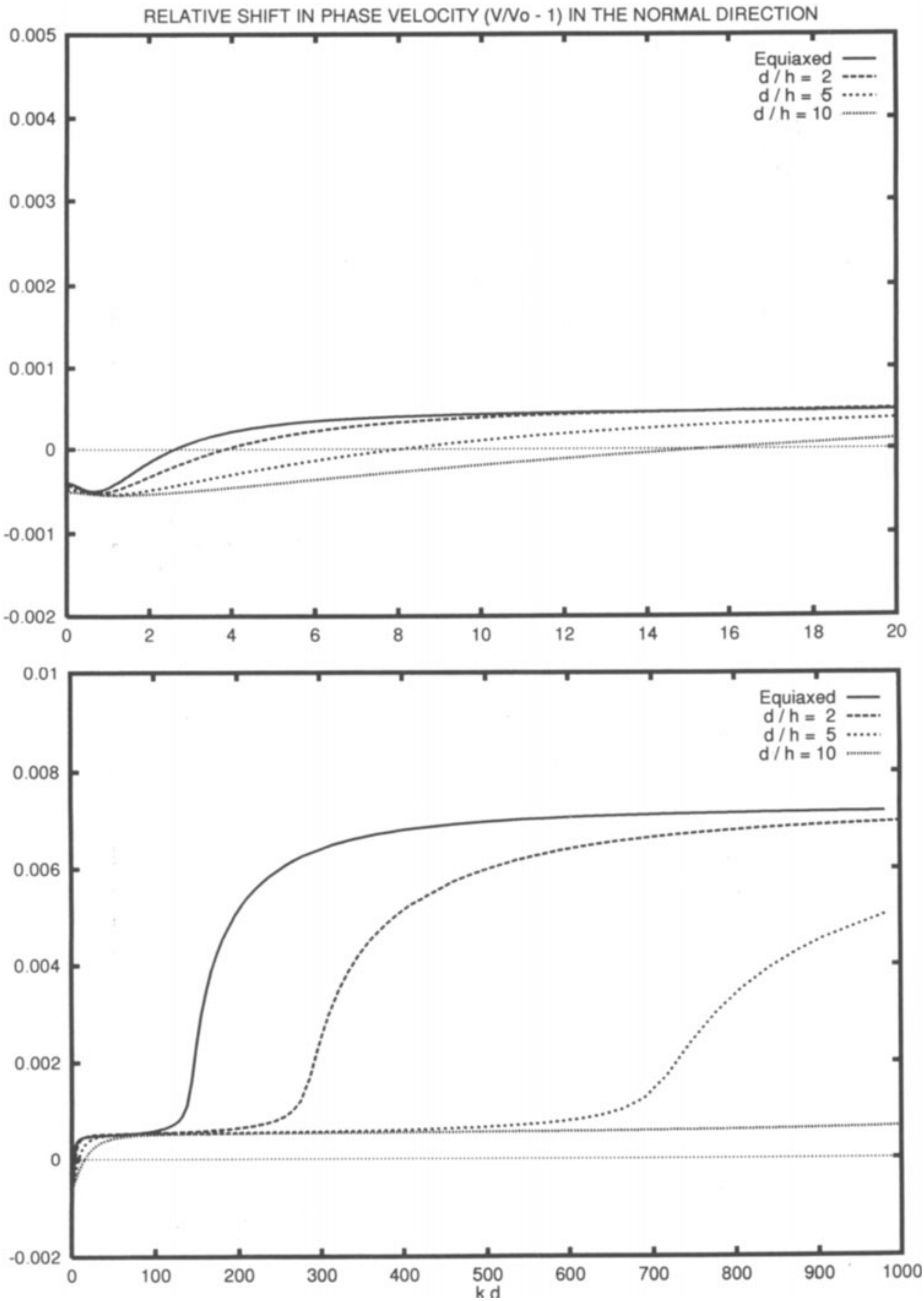

Fig. 3. Normalized Velocity of Longitudinal Waves Propagating in the Normal Direction.

elongation. Figure 5 shows the corresponding effects of propagation direction and grain shape on velocity. Here the primary effect is an offset due to the anisotropic elastic constants.

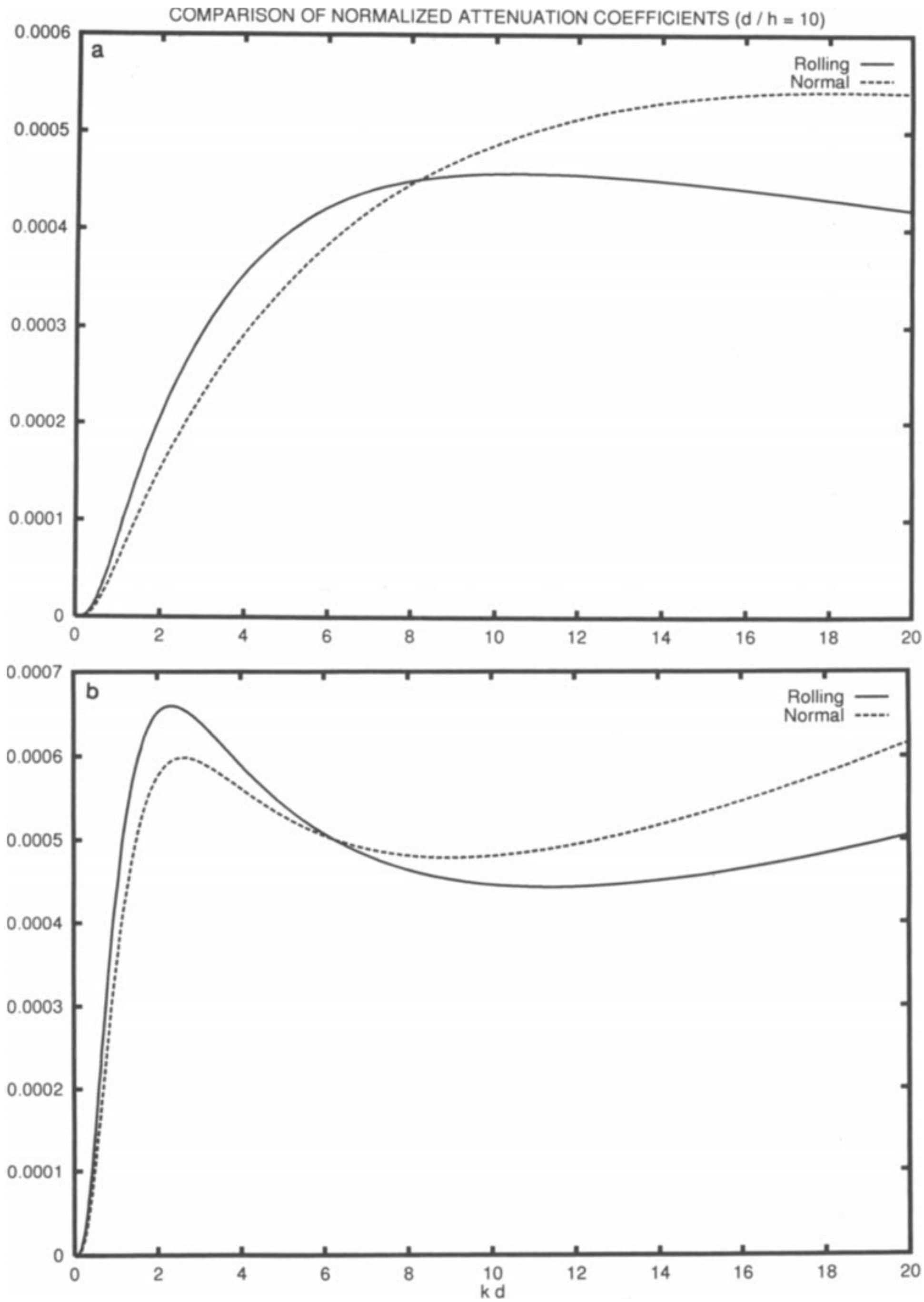

Fig. 4. Comparison of Normalized Attenuation of Longitudinal Waves Propagating in the Normal and Rolling Directions.
(a) Equiaxed Grains
(b) 10:1 Pancake Grains

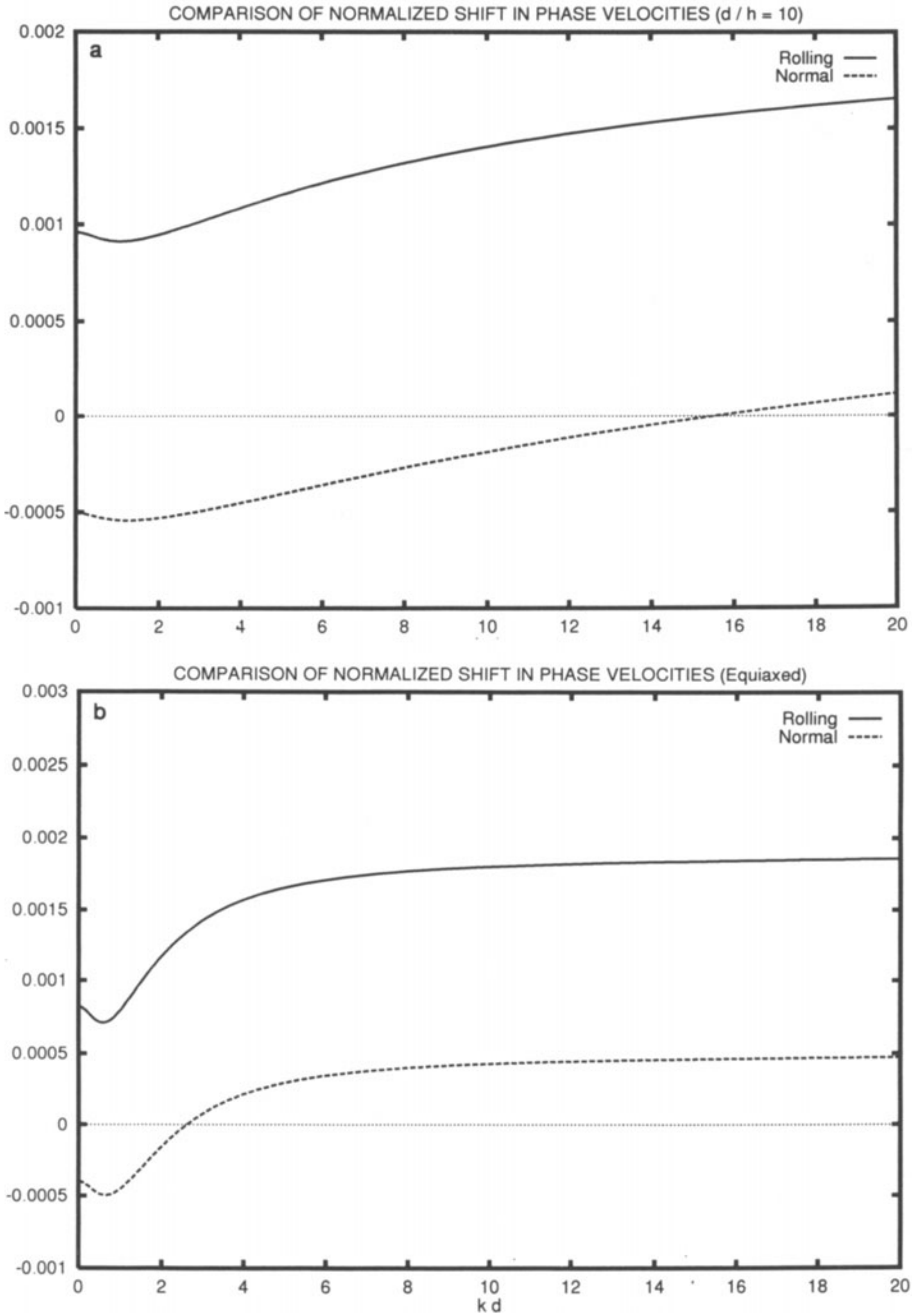

Fig. 5. Comparison of normalized velocity shifts of longitudinal waves propagating in the normal and rolling directions
(a) Equixed Grains
(b) 10:1 Pancake Grains

DISCUSSIONS

Using a stochastic wave equation, we have calculated the velocity and attenuation as a function of frequency, propagation direction, and grain shape in a textured polycrystal having properties characteristic of rolled aluminum. The results illustrate a number of important effects, e.g. how the relationship between attenuation and grain size is influenced by the grain shape. Those can serve as a basis for the interpretation of experiments in which ultrasound is used to monitor microstructure changes during processing.

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